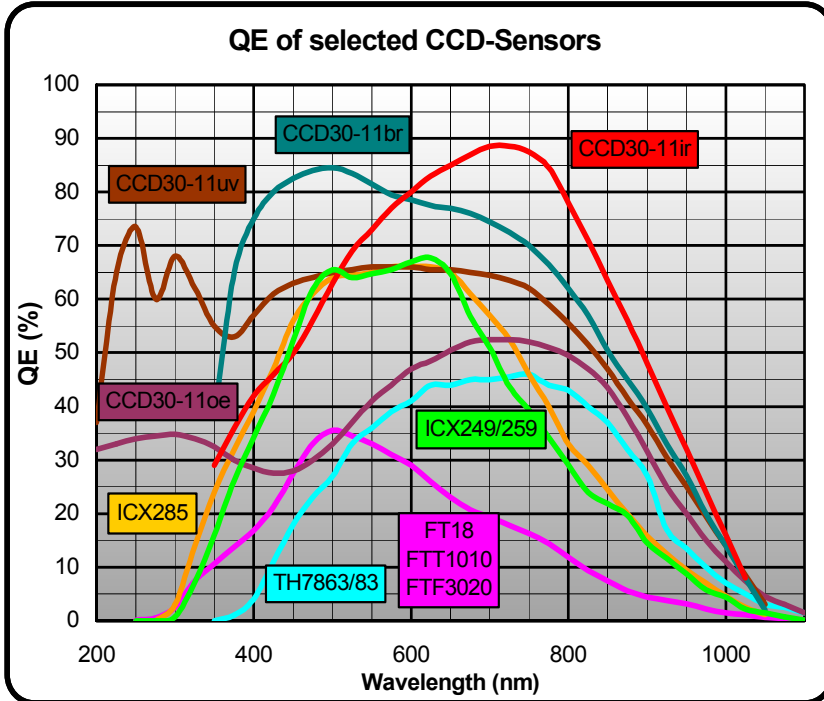




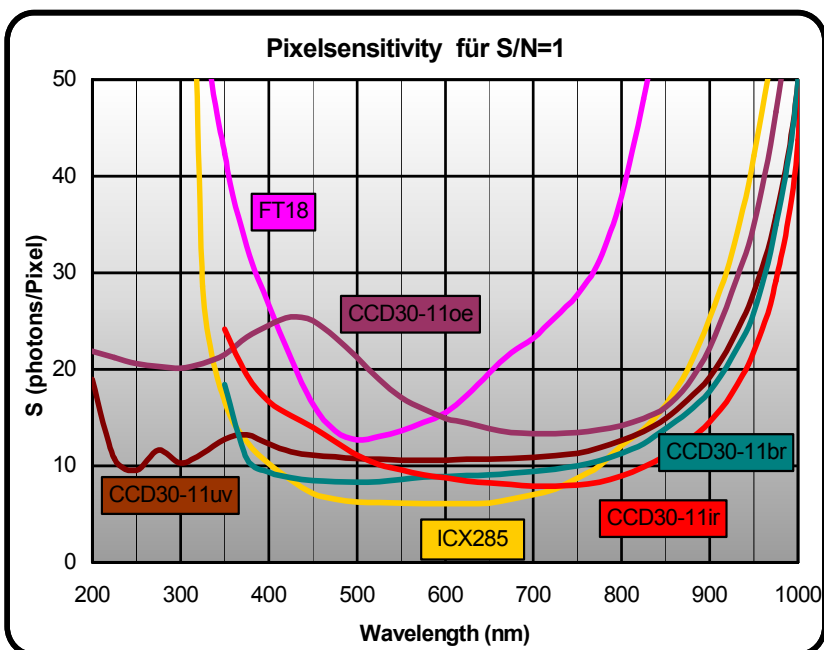
Quantum Efficiency QE



The quantum efficiency QE is defined as the percentage of the generated electronic charges by the incoming photons.

This efficiency of the CCD image sensor is determined by its material properties, production processes and its design structure. The diagram shows the wavelength dependence of the quantum efficiency of selected CCD image sensors to provide some help with the sensor selection for different applications. Open-electrode CCDs can be selected for improving the QE in the UV range due to the absorption of the polysilicon gates, back illuminated CCD sensors with different wavelength optimized antireflection coatings or front illuminated sensors.

Light Sensitivity



The light sensitivity S is the measure of a CCD image sensor's sensitivity.

It is defined as the number of photons which are necessary to generate a signal that corresponds to a signal to noise ratio of SNR=1. Particularly at low light intensities you should choose a CCD image sensor with high sensitivity.

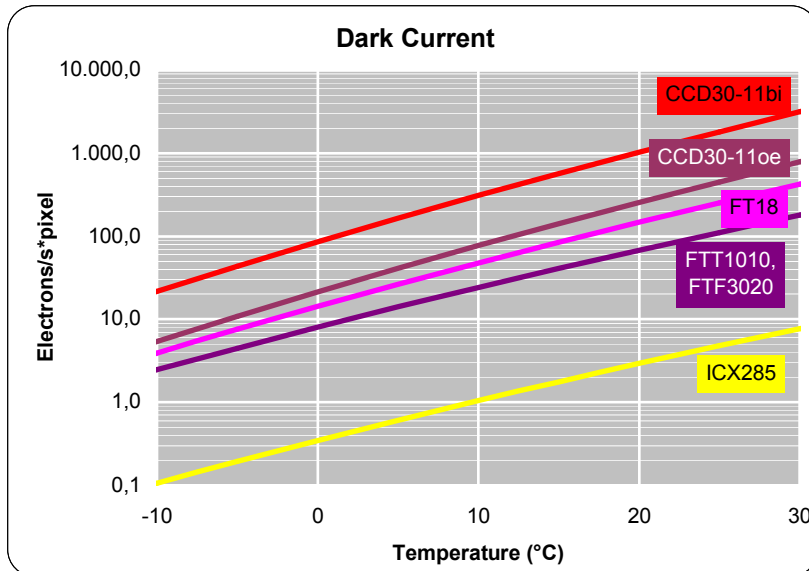
The light sensitivity is defined as the ratio of SNR and the quantum efficiency QE:

$$S = \text{SNR}/\text{QE}$$

The diagram shows sensitivity independence of the wavelength for the Scientific Imaging Systems SIS equipped with different CCD image sensors. The light sensitivity is important when selecting a camera system for applications in the low light level region.



Dark Current



The dark current of a CCD image sensor is an important factor for sensitivity.

It results from the temperature-depending thermal generation of electrons. The nearly exponential behaviour of this dependence can roughly be calculated as a doubling of the dark current with every 6°C to 9°C temperature rise, shown in the diagram for different CCD image sensors.

The dark electrons added to the electrons generated by photons and their statistical dark noise contributes to the total noise.

The dark signals are not spread regularly over the pixel array but vary due to inhomogeneities during the sensor production process. The structure of the resulting dark image is called "fixed pattern noise". Moreover there are sometimes even some "hot pixel" that have a far greater dark signal than the average CCD sensor. The fixed pattern noise and the hot pixel

can be corrected by subtracting the dark image from the measuring image.

For minimizing the dark current, the CCD camera systems of THETA SYSTEM are peltier cooled by default.

Full Well Capacity, FWC

The full well capacity FWC is the maximum number of electrons which one pixel can contain before its saturation. The FWC depends mainly on the size of the pixel, the kind of CCD image sensor and its operating characteristics. In ordinary CCD devices, electrons over the saturation charge flow to the adjacent pixel with a resulting effect called blooming which influences the qualitative and quantitative imaging performance.

CCD camera systems with anti-blooming image sensors drain these overexposed electrons to special structures with an efficiency factor of 200 to 1000 above the full well capacity. This is very important for the measurement of very low intensities near high intensity regions. These structures take up space on the CCD image sensor and thereby lower the quantum efficiency QE and/or the fill factor of the sensor.

Total Electron Capacity, TEC

The total electron capacity TEC of a CCD image sensor is the product of the full well capacity FWC and the total number of pixel. TEC is a good measure for the comparison of different CCD image sensors in consideration of the total noise electrons TNE. The total dynamic TD of a CCD camera system is the ratio $TD = TEC/TNE$.



Total Noise Electrons, TNE

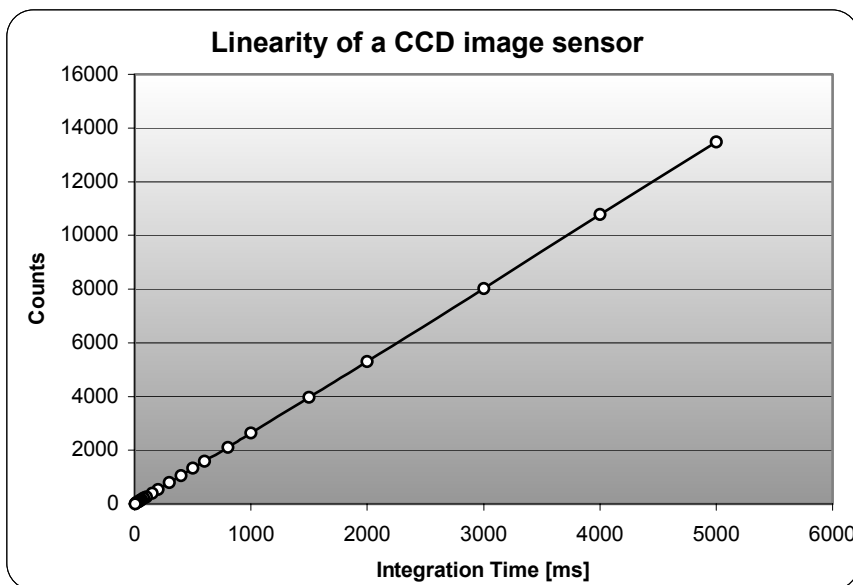
The total noise electrons TNE of a CCD image sensor is the product of the signal to noise ratio SNR and the total number of pixel. In connection with the total electron capacity TEC the total dynamic TD = TEC/TNE of the CCD camera system will be received.

Fill Factor

The fill factor is the active pixel area for the conversion of incoming photons. CCD image sensors with a fill factor of less than 100% show moiré structures due to the spatial sampling characteristics.

This behaviour influences the modulation transfer function and prevents the quantitative analysis of image intensities. In addition, the quantum efficiency will be decreased. This effect can be reduced by the "lens-on-chip" technology: Every pixel has its own lens, but with a resulting disadvantage of a direction-dependent sensitivity. The quantum efficiency decreases with the increase of the angle of incoming photons, even for values smaller than 2.8 or numerical apertures higher than of the optical systems. This is, especially in the low light level region, an important limiting factor for absolute sensitivity.

Linearity, Lin



A very important characteristic of a CCD imaging system for photometric applications is its linearity.

The digital signal should be proportional to the number of incoming photons. The linearity can be defined as the percentage of the deviation of a linear plot compared to the maximum intensity value.

$$\text{Lin (\%)} = \frac{\text{deviation} \times 100}{\text{max.signal}}$$

The linearity depends on the CCD image sensor itself, the signal processing electronics and the A/D converter. A typical linearity plot is shown in the diagram on the left side.

Our CCD camera systems have nonlinearities in the range of a few tenths of a percent.

Because the nonlinearity is nearly constant for a CCD, it can be improved down to values less than one-tenth of a percent with lookup tables. Because of that, a fast correction is possible and the quality of the CCD camera system can be raised regarding to the linearity.

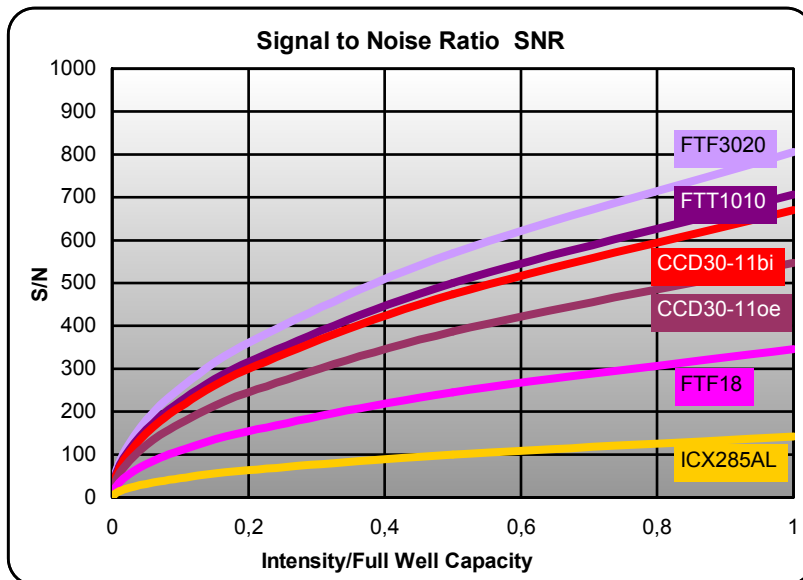


Dynamic Range

The dynamic range of a CCD camera system is defined as the ratio of the full well capacity FWC to the signal to noise ratio SNR. It is an important characteristic of the CCD camera performance. It specifies the ability to measure very dim and very bright areas and therefore the intensity range of a single image.

THETA SYSTEM uses 14-bit A/D converters with 3MHz and 10MHz readout speeds and 18-bit (16-bit used) A/D converters with 1MHz conversion speed. This high digitalization dynamic avoids the necessity to implement different detection modes for high, medium and low light levels to optimize the system for the application. Especially in the case of signal averaging over many images, the high digitalization dynamic extends the total dynamic range up to 19-bit with the 18-bit system and 15-bit with the 14-bit system, not to forget the maximum of 13-bit with a 12-bit system.

Signal to Noise Ratio, SNR



The signal to noise ratio SNR depends on:

- ▶ the natural photon statistics $\sqrt{I_s}$ of the incoming photons I_s
- ▶ the dark noise $\sqrt{I_D}$
- ▶ the read-out noise A , resulting from the CCD sensor and processing electronics.

$$\text{SNR} = I_s / \text{SqR}(I_s + I_D + A^2).$$

The diagram provides the typical SNR of CCD camera systems with the shown CCD image sensors and their full well capacity. In the region of higher intensities, e.g. in case of photometric studies, absorption + beamprofile measurements and microscopic applications, a CCD sensor with

high full well capacity should be chosen, because the SNR depends mainly on the photon statistics at intensities higher than a few percent. The dark noise and the read-out noise dominate in applications with low intensities, e.g. fluorescence, and the light sensitivity S is the selection of choice.

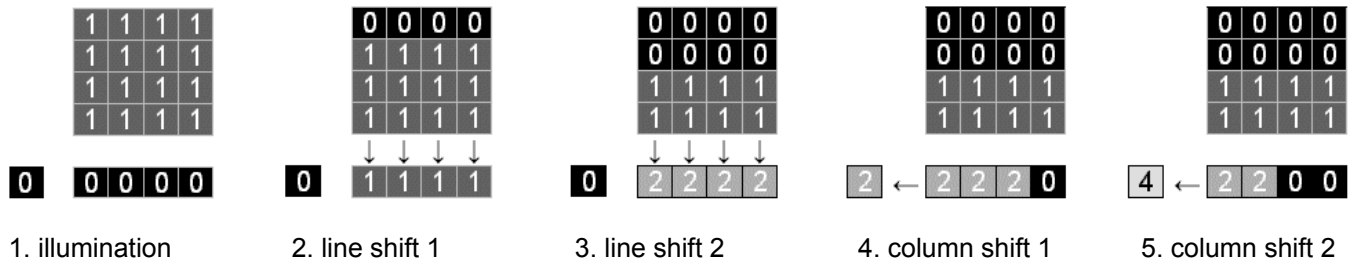
Binning

Binning is the combination of intensities of adjacent pixels into an image with a resulting lower spatial resolution. Hardware binning is the addition of generated electronic charges of several pixel directly on the CCD chip during the readout. These combined charges will be read only one time from the sensor output stage with the resulting lower read-out noise corresponding to the binned pixel number. Hardware binning is therefore convenient for low intensities when the reduced spatial resolution can be tolerated. It is very important to take care of the maximum electron capacity in the readout register and the output stage due to blooming effects. Software binning is the addition of adjacent pixel intensities in the image memory after the image acquisition. The summarization increases the number of electrons of one image element and therefore the signal to noise ratio SNR corresponding to the square root of the number of binned pixels. Hardware binning of sensor lines lowers the read-out time and therefore speeds up the frame rate. Intelligent combination of the hard- and software binning factors results in a good compromise between spatial and time resolution for image capturing of time-dependent image sequences.

Glossary



Schematic cycle of a 2x2 hardware binning of a 4x4 CCD-Matrix:



After illumination of the single pixel with the relative intensity of 1, the charges of all lines will be transferred with the line shift 1 one step towards the output register. The charges of the lowest line are now inside the output register and the uppermost line contains no charges. In a similar way the line shift 2 happens, and the charges of the lowest line will be added to the charges in the output register. Simultaneously the transfer processes occurs with the column shift 1 and column shift 2 into the output stage. The resulting intensity of 4 will be read out of the output stage by the camera electronics and with the following reset the system is ready for the next cycle.